AD-A182 400 FREQUENCY STABILIZATION AND PHASE LOCKING OF LASER DIODES AND LASER ARRAYS(U) NAVAL RESEARCH LAB WASHINGTON DC OPTICAL SCIENCES DIV L GOLDBERG 1986 1/1

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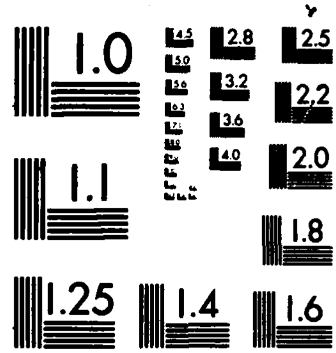

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AD-A182 400

OPTICAL SCIENCES DIVISION OF
NAVAL RESEARCH LABORATORY
WASHINGTON, DC 20375

FY 87 Progress Report

Frequency stabilization and Phase Locking of Laser Diodes and Laser Arrays

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Code 6572

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The major accomplishments for FY 86 were:

1. Demonstration of efficient coupling of an injection locked laser array single lobe output into a single mode optical fiber. A coupling efficiency of 30% was achieved for a 40-element array emitting 500 mW, corresponding to a fiber output power of 150 mW.

2. Demonstration of a novel external ring laser cavity operation of a gain guided array. The ring cavity relies on self-injection locking of the array by its own spatially filtered output. As in the case of injection locking, the ring laser external cavity results in single diffraction limited lobe far field emission of the array, but with the added advantage of eliminating the need for a separate master laser and the associated wavelength and temperature requirements.

These research results are described in detail below.

1. Coupling of laser array emission into a single mode fiber.

As has been demonstrated in FY 86 and FY 85, injection locking of gain guided laser arrays produces single lobe emission with the lobe width equal to the diffraction limit for a particular array aperture width. The diffraction limited single lobe far field emission corresponds to an apertured planewave emission in the near field. Some applications such as free space communications, acoustooptic signal processing and non-linear optics require collimated and circularly symmetric beams with little phase or intensity distortion. Such beam can be obtained by spatially filtering diode laser output using a pinhole or a single mode optical fiber.

In this section the experimental results of coupling the output of an injection locked 40-element gain guided array into a 5 μm polarization holding single mode fiber are described. the relatively high 30% coupling efficiency obtained is comparable to that which has been demonstrated with single stripe

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laser diodes and shows that the injection locked array near field emission contains relatively little phase and intensity distortion. Injection locking and fiber coupling were carried out using the optical arrangement in Fig. 1. The array was a commercially available 40-element gain guided device fabricated by Spectra Diode Laboratories. A single-stripe, single-mode, Hitachi HLP 1400 laser, emitting at 0.82 μm and within several longitudinal mode spacings of the multimode array spectrum was used as the master laser. As was the case with 10 and 20 - element arrays, in order to achieve injection locking with minimum injected power, the injected beam was shaped by a cylindrical lens so that at the array facet its width was approximately equal to 400-μm emission near field width of the array. In addition, the injected beam was titled by $\theta = 4°-5°$ (Fig. 1) in the plane of the laser junction, relative to the facet normal. These conditions, required for optimum injection locking, can be considered to result in maximizing of the coupling efficiency of the injected beam into one of the two dominant plane waves which comprise the array spatial modes. When injection locked, the array emitted in a single far field lobe which was offset by about 4.5° from the facet (Fig. 2). The off-normal angle offset of the array lobe had an equal magnitude and an opposite polarity to the injected beam angle (Fig. 1). Since the far-field lobe represents an apertured plane wave in the near-field emission, the array can be seen to represent a reflective laser amplifier for the injected apertured plane wave, with a unique property of non-normal incidence and emission, as described in FY 86 report and publications.

Unlike the case of single stripe reflective laser diode amplifiers where the input and output beams are collinear, in the case of the array, the ~ 9.0° angular separation between the input and output beams allows for their spatial separation. The reflective amplifier operation of the array also makes it possible to use a single set of lenses for the dual purpose of converting the circular master laser beam into a slit-like shape, as well as shaping the array emission into a beam of circular cross section necessary for efficient fiber coupling. In Fig. 1 the emission of the injection locked array (dashed lines) is converted into a circular beam by a short focal length spherical lens L_1 lens and the cylindrical lens. These also focus the array output at a position which is laterally displaced, by several milimeters, from where the injected beam is focused near the isolator. For coupling into the fiber, the array output beam is intercepted by a mirror and then focused by spherical lens L_3. Focusing of the injected beam emerging from L_4 is necessary to maximize transmission through

the small aperture of the isolator. Because of the spatial separation between the injected and the emitted beams, the isolation requirement is greatly reduced. The need for an isolator is not completely eliminated however, since although most of the injection locked array power is emitted close to the angle of the main lobe, with the array biased above threshold, a small amount is also emitted in the direction parallel to the injected beam.

Coupling of the array output into a single-mode fiber was carried out with the array far-field distribution as shown in Fig. 2. The array was biased at 1.6 I_{TH} corresponding to an output power of P_0 = 510 mW, while the injected power incident on the array was P_i = 11.0 mW. A measured FWHM single lobe width of 0.13° corresponds to 1.25 times the diffraction limit for a 400-μm aperture. The small deviation from the diffraction limit is primarily attributed to non-uniformity in the near-field intensity across the array aperture. As shown in Fig. 2, without injection, the array exhibited a wide double-lobed far field which is characteristic of these types of devices. Changes in the array emission spectrum were also observed, where injection locking changed the array spectrum from multimode to singlemode, with a dominant to next-highest mode ratio of approximately 20 dB.

The total array to fiber coupling efficiency is given by $C = C_0 C_m C_r$ where C_0 = 0.78 is the array to fiber transmission of the optical system in Fig. 1, which included the efficiency of lens L_1 in capturing the array emission cone, C_R = 0.92 accounts for reflection loss at fiber facets, and C_m is the coupling loss due to mismatch between the field distributions of the focused spot produced by lens L_3 and the fiber mode. A maximum single-mode fiber output of 150 mW was obtained, corresponding to an overall coupling efficiency of C = 0.30 and a coupling loss due to mode mismatch of C_m = 0.41. A major part of the field mismatch loss can be attributed to the fact that some of the array emission is at angles outside of the main lobe, Fig. 2. At the focal plane of lens L_3, this part of array emission will be focused away from the central spot produced by the main lobe and hence will not be coupled into fiber core. Furthermore, improvements in the coupling efficiency are expected by increasing the injected power and improving the optical system.

In summary, 150 mW of a 500 mW output from an injection locked laser array was coupled into a single mode fiber. This represents the highest reported power coupled from a semiconductor laser source into a single mode fiber.

2. Single lobe operation of a laser array in an external ring laser cavity.

In this section a new technique of self-injection locking of a coupled stripe array by its own spatially filtered output, resulting in a single diffraction limited lobe emission is described. The method is based on an array-external ring cavity laser configuration which combines the injection locking/amplification properties of the array with spatial filtering of the array output by a single mode fiber. The technique produces diffraction limited lobe widths characteristic of injection locked arrays while eliminating the need for a separate master and associated wavelength stability requirements.

The external ring laser configuration, shown in Fig. 3, utilizes the same optical system as that previously used to injection lock a 40-element array, and couple its output into a singlemode fiber. In the ring cavity case however, instead of the master laser the output of the single mode fiber itself is used as the injection beam source. The output end of the fiber is positioned near the focal plane of lens L4 which focuses the fiber output through a Faraday polarization rotator (Faraday isolator with polarizers removed). The injected beam is shaped by a cylindrical lens L2 and a spherical lens L1 so that it matches the array near field at the facet, and its incidence angle is offset by several degrees from the facet normal in the junction plane. These conditions are optimum for obtaining single lobe array emission with minimum injected power.

Because of their angular separation, the input and output beams are spatially separated in front of the Faraday rotator in Fig. 3. A mirror and lens L3 are used to couple the output beam into the single mode polarization holding fiber, thereby completing the external ring laser loop. In order to extract power out of the loop, a polarization preserving fiber coupler was used as shown in Fig. 3, or a beamsplitter was placed between L4 and the Faraday rotator. In both cases the output beam was ofc a near-gaussian cross section as defined by the fiber mode.

The far field pattern of the array in external cavity operating at a free running power of 500 mW (I/I_{TH} = 1.6) is shown in Fig. 4. With the optical feedback path blocked, the array operated with a characteristic double lobe far field, Fig. 4. A measured lobe width of 0.13° (FWHM) was within the measurement accuracy of a 0.10° diffraction limit for a 400 μm wide uniform aperture. The 7.0° off center lobe position was one which produced the greatest output powers from the single mode fiber. Positive or negative lobe emission angle, corresponding to up or down directed array output beam in Fig. 3 could be

obtained depending on the angular position of the half-wave plate. Each case occurred when the power flow in the ring cavity was counterclockwise or clockwise respectively. A 45° polarization rotation in the Faraday rotator resulted in an injection beam polarization which was parallel to the array junction for either one of the flow directions and orthogonal for the other, as determined by the halfwave plate rotation. Ring cavity oscillation occurred for the power flow direction and lobe emission angle which had sufficient gain to overcome cavity loss. The polarization mismatch for the opposite flow direction and a corresponding reduction in gain prevented oscillation in that direction, resulting in no array output power in the associated lobe and therefore highly single lobe far field distribution.

The array emission spectrum observed with the single lobe output of Fig. 4 was single mode (Fig. 5) with a side mode extinction ratio of more than 40 dB. Figure 5 shows two Fabry-Perot orders. At high array output powers, (> 300 mW) singlemode or multimode operation could be obtained by proper adjustment of the optical phase delay of the external cavity. With multimode emission, the far field lobe became significantly wider than in the single mode case and the power coupled into the single mode fiber decreased. The exact nature of the spectral selection process in the array ring cavity laser will be further investigated.

The external cavity can be considered to as a ring laser with the array providing sufficient gain for the incident beam to overcome external cavity losses (including array coupling loss and fiber coupling loss). Maximum output power P_0 of the array ring cavity can be extracted by optimizing the optical transmission T_2 of the fiber coupler. The optimum value of T_2 depends on the gain vs. output power saturation characteristics of the array. In the experiment carried out, a non-optimum value of $T_2 = .67$ was used resulting in $P_0 = 90$ mW emitted by the output port of the fiber coupler. The array was operated at a free running output power of 500 mW.

In summary, a new type of a external ring cavity for a laser array was demonstrated. The cavity arrangement is equivalent to self-injection of the array by its own spatially filtered output. Single lobe emission and single mode spectrum obtained with the ring cavity are similar to those achieved with external injection locking. In the external cavity case however, the need for an external master laser and wavelength/temperature stabilization is eliminated.

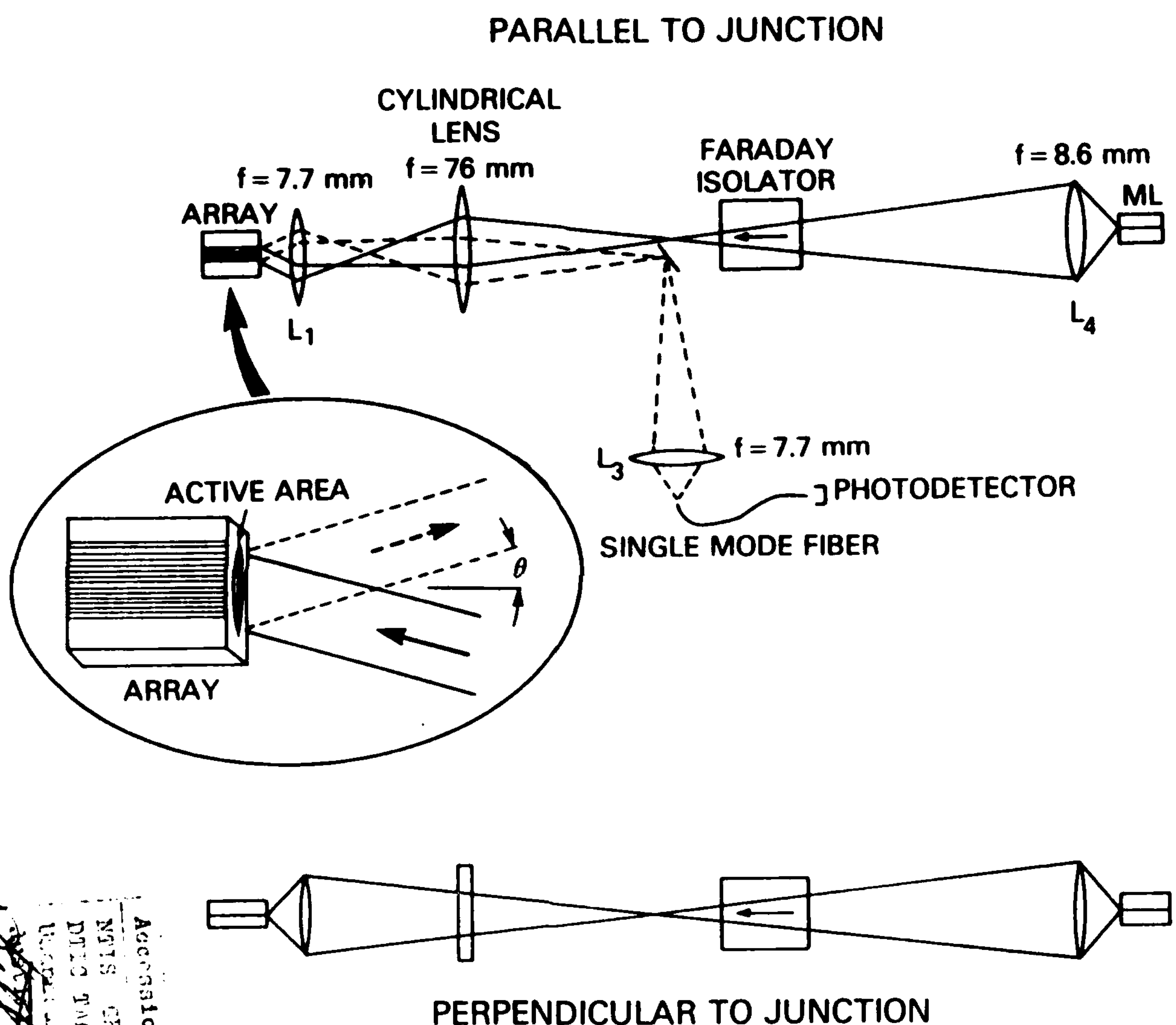

PARALLEL TO JUNCTION
CYLINDRICAL
LENS
f = 76 mm
f = 7.7 mm
ARRAY
L1
FARADAY
ISOLATOR
f = 8.6 mm
ML
L4
L3
f = 7.7 mm
PHOTODETECTOR
SINGLE MODE FIBER
ACTIVE AREA
ARRAY
θ
PERPENDICULAR TO JUNCTION

FIG 1

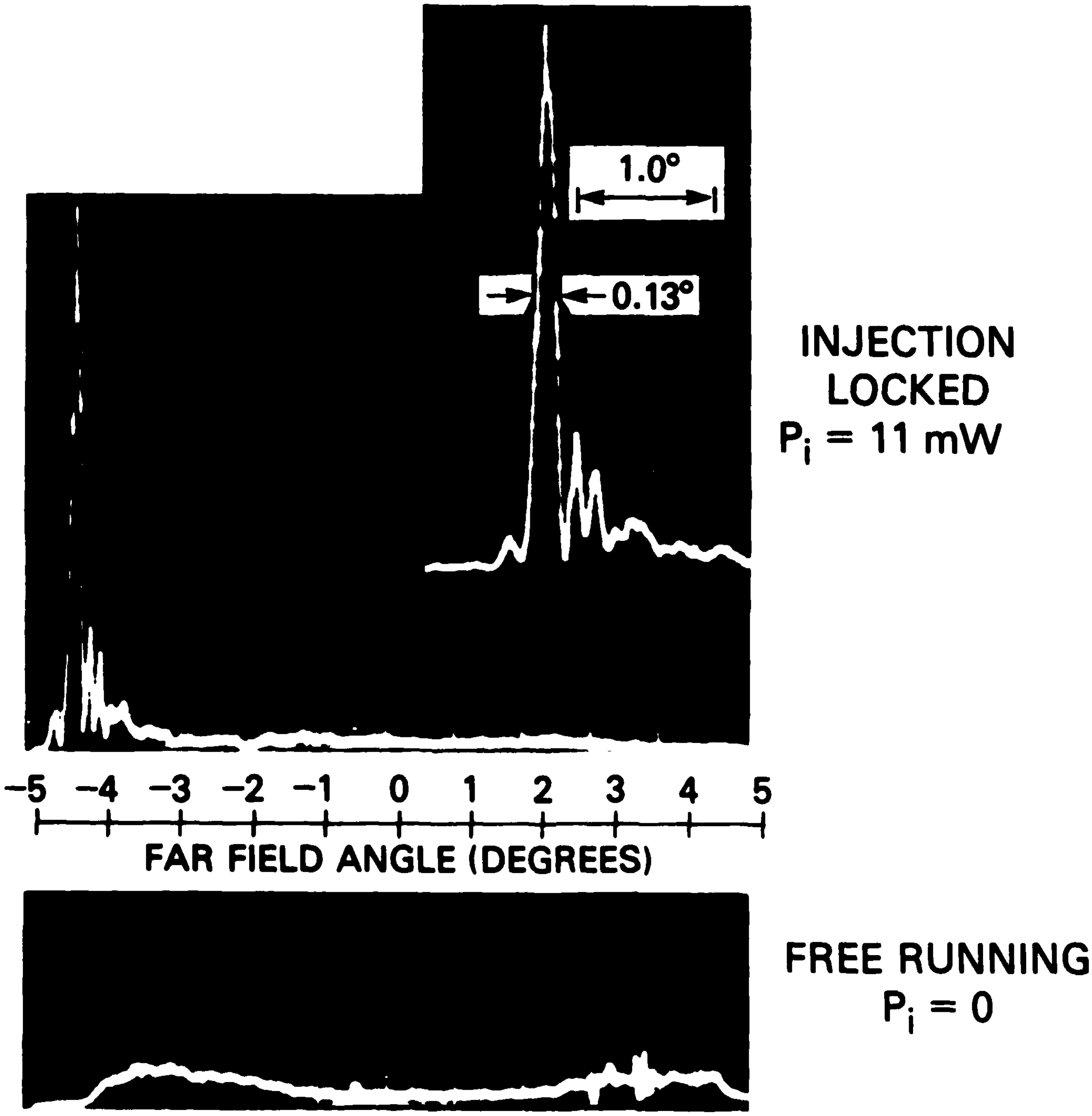
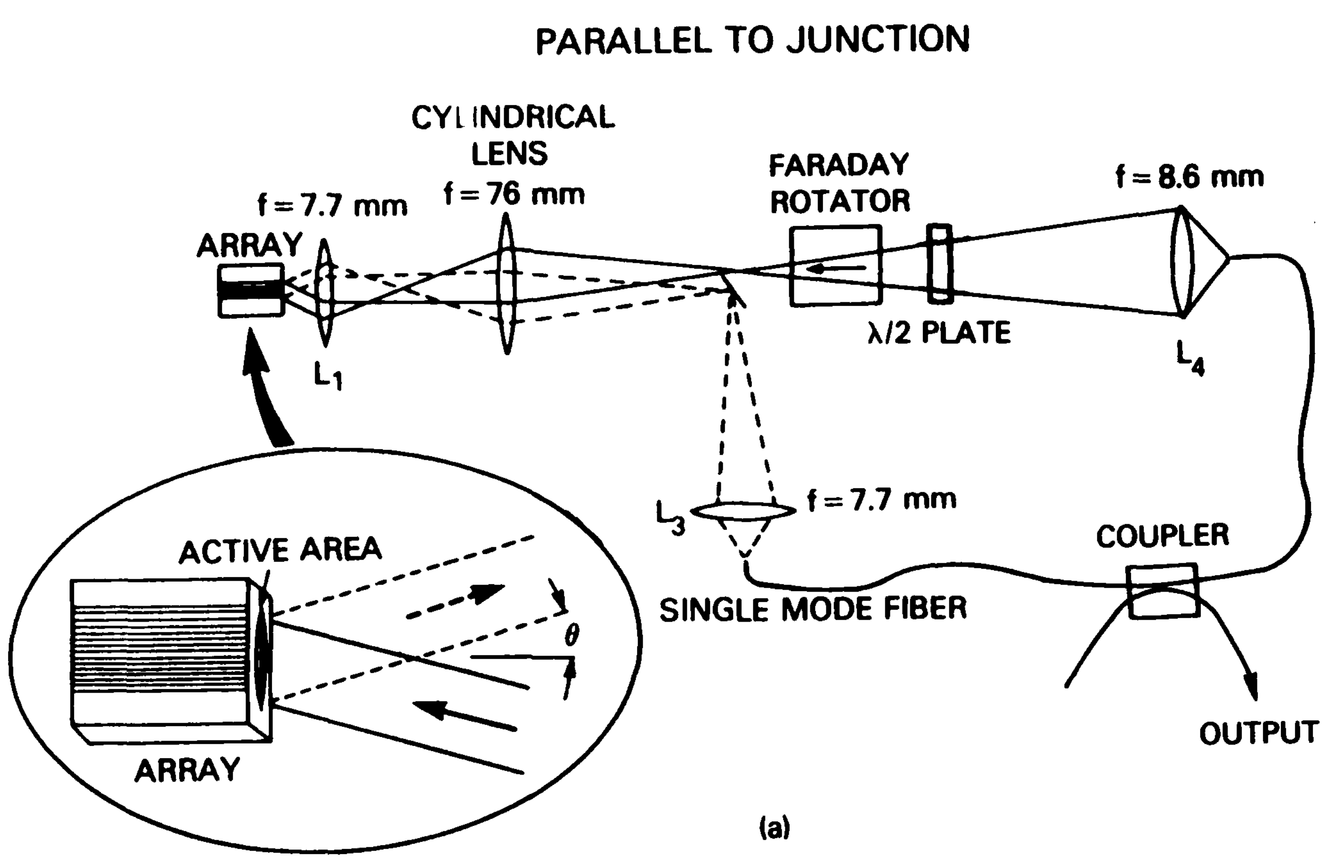
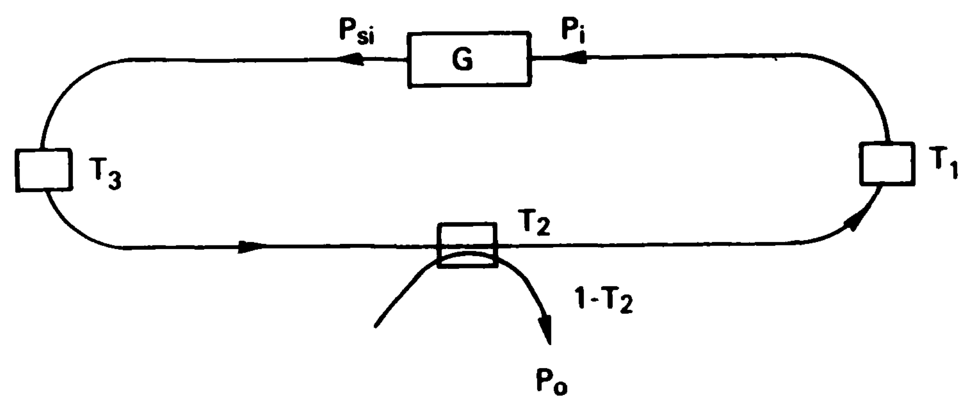

1.0°
0.13°
INJECTION LOCKED
P_i = 11 mW
−5 −4 −3 −2 −1 0 1 2 3 4 5
FAR FIELD ANGLE (DEGREES)
FREE RUNNING
P_i = 0

FIG 2



PARALLEL TO JUNCTION
CYLINDRICAL LENS
f = 76 mm
f = 7.7 mm
ARRAY
L1
FARADAY ROTATOR
λ/2 PLATE
f = 8.6 mm
L4
ACTIVE AREA
ARRAY
θ
L3
f = 7.7 mm
SINGLE MODE FIBER
COUPLER
OUTPUT

(a)



Psi
G
Pi
T3
T1
T2
1-T2
Po

(b)

FIG 3

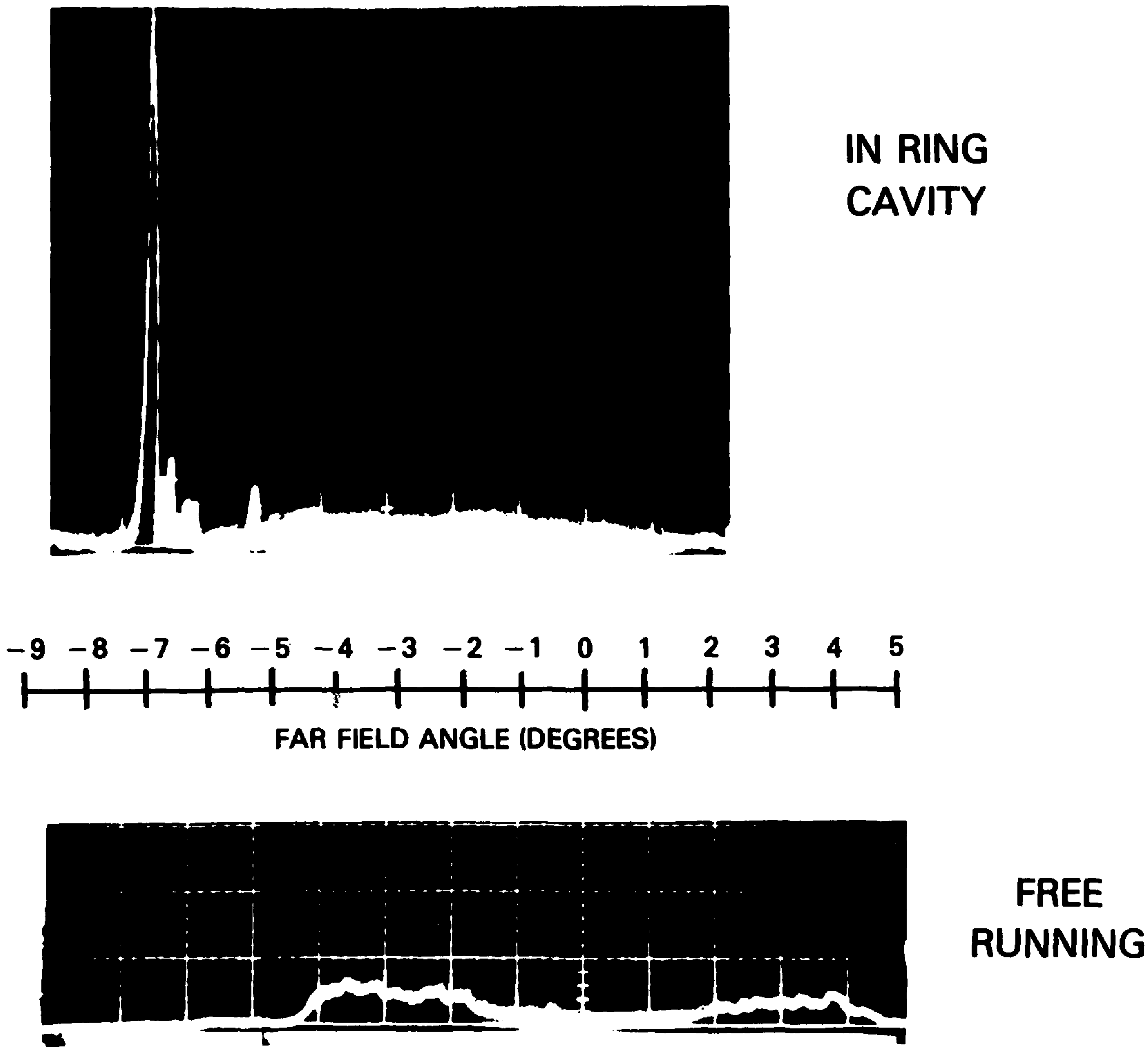
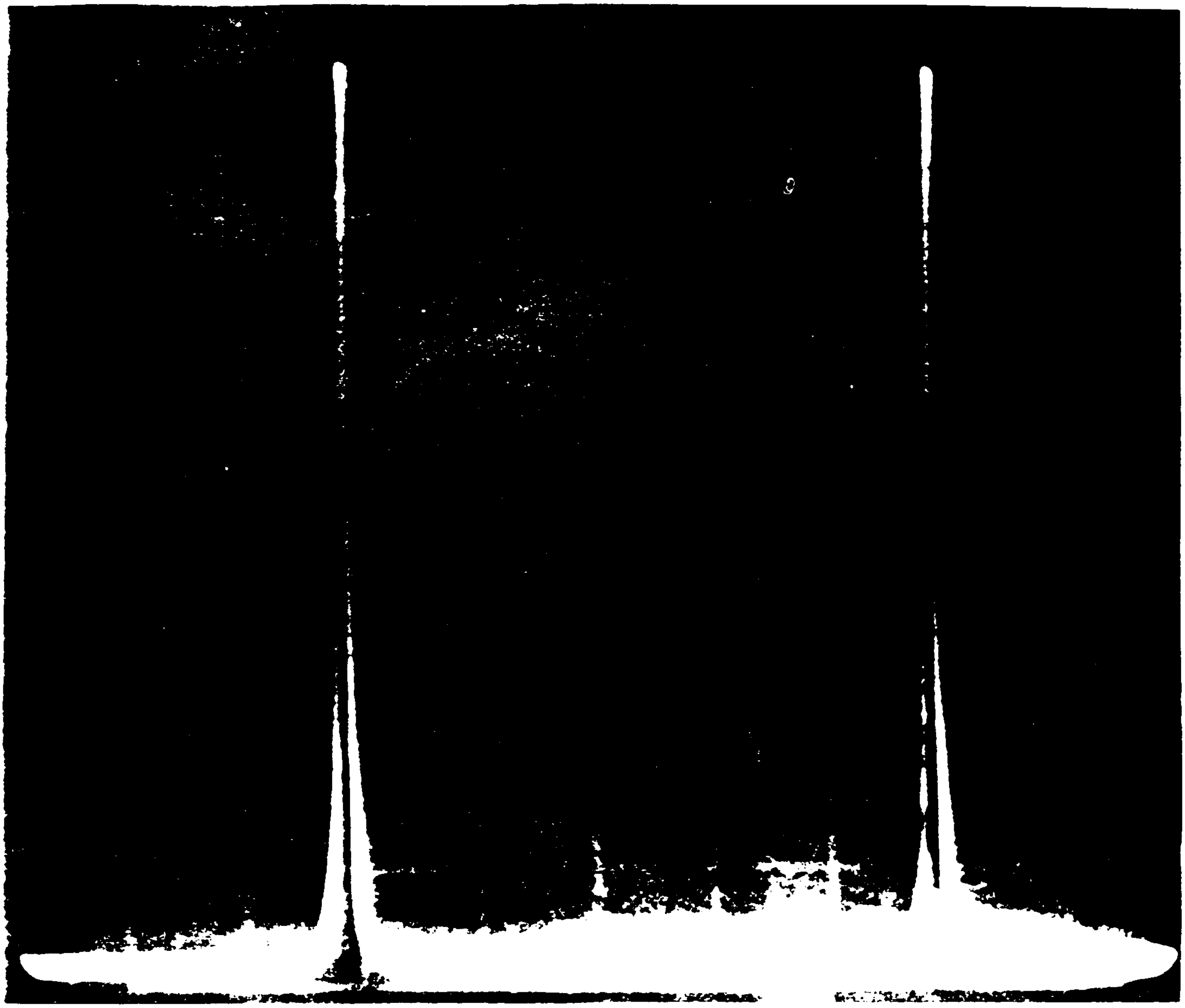

IN RING
CAVITY
−9 −8 −7 −6 −5 −4 −3 −2 −1 0 1 2 3 4 5
FAR FIELD ANGLE (DEGREES)
FREE
RUNNING

FIG 4



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